Characterisation of silicon photomultipliers for the upgrade of the LHCb RICH detectors (*)(**)

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Summary. — The LHCb Upgrade 2, designed for the High-Luminosity programme, poses significant challenges for the Ring Imaging Cherenkov (RICH) detectors. This paper investigates the feasibility of replacing the current photodetectors with silicon photomultipliers (SiPMs). SiPMs offer improved timing and spatial resolution but require careful control of dark count rates (DCR), temperature sensitivity, and radiation-induced effects. The characterisation procedures and experimental setups are presented, as well as preliminary results from laboratory and beam test, providing insights into the operating conditions required to fully exploit SiPMs in high-radiation environments.

1. – Introduction

The High-Luminosity program of the LHC will result in a significant increase in the instantaneous luminosity provided to the LHCb experiment to about 1.0×10^{34} cm^{-2} s^{-1}, corresponding to approximately 40 interactions per bunch crossing. To ensure that the LHCb detector continues to perform excellently under these harsher conditions in terms of radiation hardness and detector occupancy, the RICH subdetectors must be upgraded. The LHCb RICH Upgrade II [1] [2], scheduled during LHC's Long Shutdown 4 (LS4), will require to improve the reconstructed Cherenkov angle resolution, to increase the spatial granularity and to introduce the timing information, as well as excellent radiation hardness and high photon detection efficiency. In order to achieve this, improvements are planned in the optical mirror system and the photodetector planes. Specifically, it is crucial to maintain the RICH occupancy below 30% and to measure the photon time of arrival with sub-100 ps resolution, narrowing the viable photosensor candidates to replace the multi-anode photomultiplier tubes (MaPMTs) currently in use [3].

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2. – Properties and challenges of silicon photomultipliers

SiPMs consist of an array of single avalanche photodiodes (SPADs) operated in Geiger mode, each coupled to a quenching resistor. Compared to MaPMTs, SiPMs offer:

- **High granularity:** pixel sizes of 1.4×1.4 mm^2 or 2×2 mm^2, enabling fine angular resolution.
- **Fast timing:** intrinsic timing resolution in the sub-100 ps range.
- **High Photon Detection Efficiency:** important for single-photon applications like RICH detectors.
- **Compactness and robustness:** solid-state devices are less bulky and more mechanically stable than vacuum tubes.
- **Magnetic field immunity:** essential for operation in the residual LHCb magnet field.

However, SiPMs also pose challenges such as:

- **Dark Count Rate (DCR):** thermally generated carriers produce noise pulses, indistinguishable from real single-photon signals. The DCR increases exponentially with temperature and is further increased by radiation exposure.
- **Radiation damage:** induces defects in the silicon lattice of the sensor, increasing leakage current and DCR.
- **Cross-talk and afterpulsing:** degrade the signal-to-noise ratio.

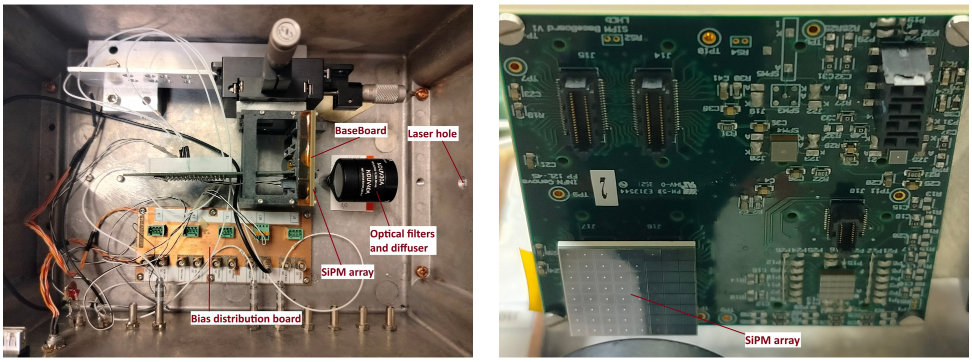
These limitations necessitate extensive characterisation and development of mitigation strategies, particularly for long-term operation in a highly irradiated environment such as LHCb.

3. – Experimental setup for time resolution characterisation

A controlled laboratory setup, shown in fig.1, was built to perform the characterisation of different key parameters of SiPMs. A fast pulsed laser was used to generate photons in a sealed dark box containing a Hamamatsu S13361-2050AE-08 SiPM array, which could be placed in a climatic chamber to characterise the sensors at different temperatures [4]. The same setup was used to measure the intrinsic timing performance of the SiPMs. The timing measurements were referenced to the laser trigger. The SiPM output signals were digitized, and two key parameters were extracted:

1. **Time of Arrival (ToA):** the time difference between the SiPM signal and the laser trigger.
2. **Time over Threshold (ToT):** the duration for which the signal remains above a fixed threshold.

A correction for time walk was applied based on the correlation between ToA and ToT, allowing for improved resolution in single-photon events. Gaussian fits to the corrected ToA distributions yielded timing resolutions down to approximately 116 ps, as shown in fig.2, in agreement with expectations for SiPMs.



(a) (b)

Fig. 1. – The view of the setup inside the dark box (a) and the PCB housing the SiPM array (b).

4. – Testbeam validation at CERN SPS

To validate laboratory findings in a realistic environment, SiPMs were tested on a particle beam at the CERN SPS. The beamline was instrumented with various photodetectors, including a micro-channel plate (MCP) photomultiplier with 20 ps time resolution for timing reference. The SiPMs, mounted with FastIC readout electronics [5], were exposed to the Cherenkov photons of a controlled flux of pions at 180 GeV.

Data were collected at various overvoltages, from V_{br} + 1 V to V_{br} + 7 V, and threshold settings, from 5 to 20 ADC steps below the signal pedestal (pn), with the signals considered negative. A comparison between some ToA vs ToT plots at different

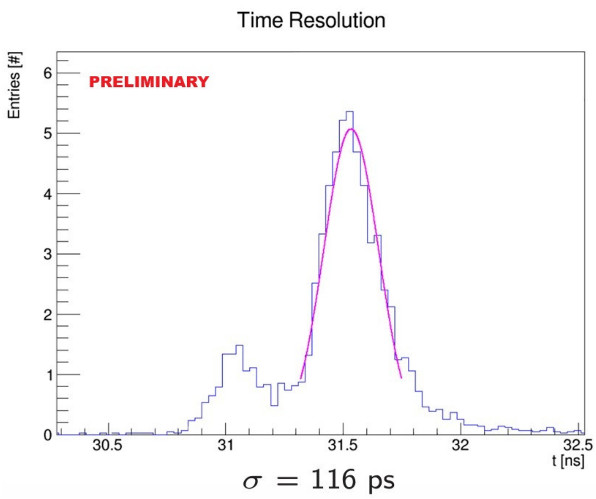


Fig. 2. – The plot shows the distribution of the time difference used to estimate the time resolution. The small bump on the left is probably due to a spurious effect, such as crosstalk from a neighbouring channel or reflection of the laser light.

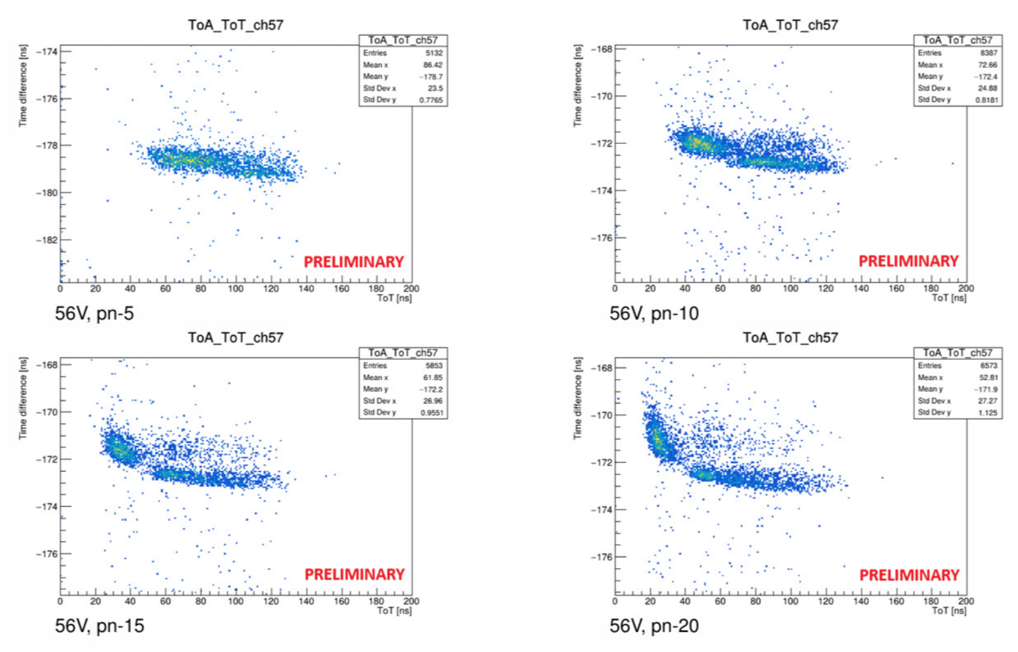


Fig. 3. – ToA vs. ToT plots for four different FastIC thresholds. The correlation between ToA and ToT worsens at higher threshold values, leading to worse time resolutions.

threshold values, indicated as pn-5, pn-10, pn-15 and pn-20, is shown in fig.3. Timing measurements were performed similarly to the lab setup, with ToA values extracted relative to the MCP signal. Gaussian fits to the corrected distributions revealed time resolutions on the order of 200 ps, as shown in fig.4, strongly depending on the operation point defined by the voltage and threshold settings.

These results show that SiPMs have the potential to meet the timing requirements for RICH Upgrade II under realistic conditions. While further improvement is required, the possibilities are promising if an optimal working point is found and noise suppression is enforced.

5. – Temperature dependence and radiation effects

Subsequently to the setup described in the sec.**3**, SiPMs were further characterised across a wider temperature range using a liquid nitrogen cryostat, covering +25°C to approximately −190°C. A total of 75 devices from five models were tested. Key results include:

- **Breakdown voltage (V_{br}):** increases with temperature at a rate of 50 mV/°C, as expected from literature, fig.5(a).
- **DCR:** exhibits exponential dependence on temperature, fig.5(b); cooling is essential to suppress this noise.

These findings reinforce the necessity of operating SiPMs at low temperatures in the

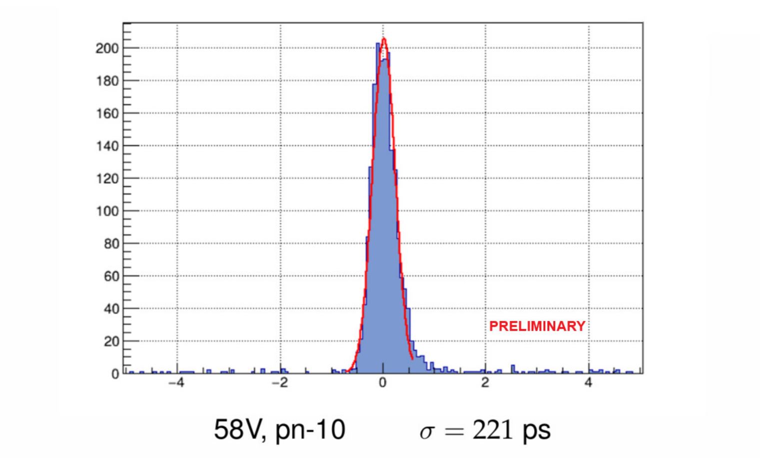


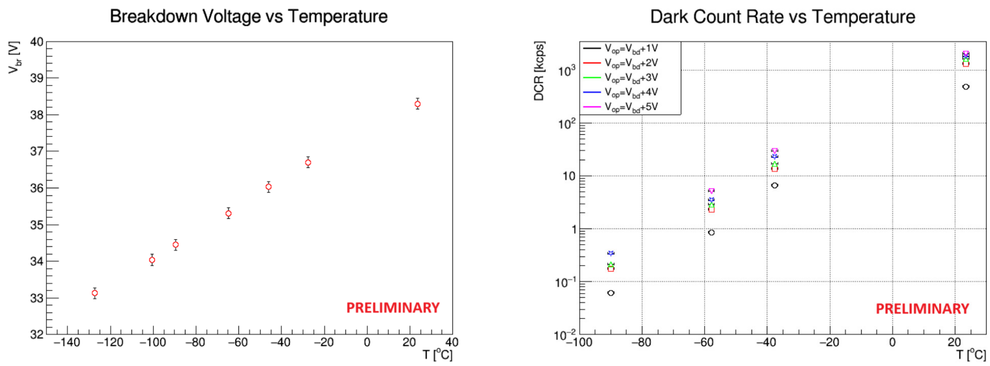
Fig. 4. – Time resolution measured at the test beam.

RICH environment. Further testing on irradiated and annealed sensors will follow to assess the mitigation of the DCR.

6. – Conclusion and outlook

The characterisation campaign demonstrates that SiPMs are a promising option for next-generation Cherenkov detectors, offering superior timing and spatial resolution compared to traditional technologies. The primary challenge remains the mitigation of noise from radiation-induced effects, and the demonstration that it can be effectively controlled through cooling and annealing.

The next steps include long-term irradiation and annealing studies, integration with final readout systems, and simulation-based optimisation of the RICH optical design. Close collaboration with industry partners through the new DRD4 collaboration [6] will be crucial to developing custom SiPM solutions tailored to the demands of LHCb.



(a) (b)

Fig. 5. – Preliminary plot of the V_{br} (a) and DCR (b) dependency on temperature.

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